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System Description Document for the Anthrobot-2: A Dexterous Robot Hand

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1.0 SCOPE OF DOCUMENT

The purpose of this document is to describe a dexterous hand recently developed at NASA Goddard Space Flight Center. The hand (the Anthrobot-2) is a fully functional, tendon-driven, five-fingered robot hand. A patent on the design has been applied for. This document gives an overview of the mechanical structure of the hand, the electronics, and the system software. The appendices give further information on interfaces developed between some commercial exoskeletal gloves and the hand. Details on interfacing to the Anthrobot will be part of another document. A list of vendors for the various commercial products is included. This list does not constitute an endorsement by either the authors or the U.S. Government.

2.0 INTRODUCTION

2.1 Areas of Use

In robotic applications, the choice of end effector is a choice between special purpose end effectors and general purpose end effectors. Examples of special purpose end effectors include two-jaw grippers, motorized screwdrivers, and spray nozzles. Multifingered hands comprise the family of general-purpose end effectors. A dexterous hand has more flexibility when coping with unforeseen situations and unstructured environments than the special purpose end effectors. A robot using special purpose end effectors requires an effector for each different task. As the number of tasks grows so does the number of effectors needed. Conversely, if the end effector cannot be changed, then the manipulated object must accommodate the end effector. This may involve specialized design of the object or addition of a special attachment point to an existing design.

In contrast to the specialized end effectors, a robot with a dexterous hand can accommodate a variety of tasks more easily. We expect that the Anthrobot will find application in areas where a robot has to perform multiple tasks in an unstructured environment. A study by Mishkin and Jau [1988] discusses the advantages that a hand would have over several types of end effectors during extra-vehicular activities (EVA) in space. The Anthrobot will also be the preferred choice where unexpected events can take place. A robot hand which features anatomical consistency with a human hand will have special advantages during teleoperation.

From a teleoperation control perspective, a human will find it easier to control a robot hand which functions like his or her own hand. The closer the robot hand follows the human anatomy, the easier it will be for a person to control it. One scenario is an emergency situation where a person must be able to perform a teleop task quickly and with little previous training. In this case, the user puts on an exoskeletal system (including a glove), attaches the hand to the robot, and performs the task in an intuitive manner. Another advantage is where the environment requires human as well as robotic interaction. If the robot uses an anthropomorphic hand, the human interfaces will work for the robot. Mishkin and Jau [1988] discuss several advantages of an anthropomorphic hand when performing tasks in space.

2.2 Previous Work

Research in the design of mechanical hands dates back to at least 1960, if not earlier. Some early examples can be found in Tomovic and Boni [1962], Okada [1979], Caporali [1982], and the following U.S. patents: Gentiluomo [1967], Mullen [1972], Eroyan [1978], Pinson [1981], Zarudiansky [1981], and Richter [1986]. The number of fingers in these hands vary from three to five. Probably the most famous of the three fingered hands is that of Salisbury and Ruoff [1990]. Some more recent examples of hands with four or more fingers include the Utah/MIT hand by Jacobsen, et al. [1986], the Dexter IIIB by Smallridge [1989], the JPL four-fingered end effector by Jau [1990], the Mark-1 by Maeda [1989], and the Belgrade/USC hand described by Rao, et al. [1988] and Bekey, et al. [1990]. The Belgrade/USC hand is based on the hand by Tomovic and Boni [1962] referenced earlier. A table in Appendix C compares the Anthrobot-2 with these other five hands.

2.3 Benefits of Approach

In comparison with the hands discussed in the previous section, the Anthrobot is specifically designed for anatomical consistency with the human hand. This includes the number of fingers, the placement and motion of the thumb, the proportions of the link lengths, and the shape of the palm. The designers of the hands discussed above either ignored or compromised on these factors.

In the human hand, we have an existence proof of a structure which is capable of supporting a wide variety of dexterous manipulation tasks. The philosophy behind the Anthrobot-2 is to provide these capabilities to a robot hand by closely following the human model. This approach has clear advantages for teleoperation. It remains to be seen if the anthropomorphic model provides any advantages over non-anthropomorphic end effectors for autonomous control. However, non-anthropomorphic designs require theoretical analysis to prove that they support dexterous tasks, whereas an anthropomorphic dexterous end effector has centuries of empirical evidence to support the validity of the design approach.

2.4 Evolution of the Anthrobot

In 1988, Charles Engler built a working, five-fingered robot hand (the Anthrobot-1) for his Master's research at Lehigh University. Engler and Groover [1989] summarizes his results. Mr. Engler came to Goddard in 1988. In 1990, the Director's Discretionary Fund at Goddard provided funds to build a second-generation prototype hand (Anthrobot-2). This hand is lighter, smaller, easier to assemble, and more anatomically correct than the original. It also features improved electronics and software for servo control and computer interfacing. Two of the Anthrobot-2s (left and right hands) will be complete by the summer of 1991.

3.0 SYSTEM OVERVIEW

Figure 1 shows a drawing of the Anthrobot-2 with views from the top and side. A third auxiliary view shows the front of the palm. The hand has four fingers and a thumb. Each finger has four joints as in the human hand; two at the knuckle (lateral and vertical motion), one between the proximal and middle finger segments, and one between the middle and distal finger segments. The thumb has four degrees-of-freedom (DOF), allowing it to emulate human thumb motion. The human thumb has two joints which provide the curling action, and a saddle joint which allows the thumb to oppose the other fingers. The saddle joint actually has two degrees-of-freedom, bringing the total number of thumb DOF to four. The Anthrobot emulates the saddle joint with two pulley driven links. The placement of the links determines the fidelity of the Anthrobot thumb motion to human thumb motion.

Futaba servomotors actuate the finger and thumb joints. Radio-controlled model hobbyists use these servomotors in their model boats and airplanes. Notice that while there are twenty joints in the hand (four for each of the fingers and four for the thumb), there are only sixteen servomotors. Like the human hand, in this hand the last (distal) joint of each finger is connected to the middle joint. This reduces the controllable degrees of motion from twenty to sixteen. Further specifications on the Futaba servos are in section 6.

The servomotors actuate the fingers via a system of tendons modeled after those in the human hand. Each motor has a pulley mounted on it. Two cables (tendons) attach to this pulley. Each cable then runs through the palm to either side of a joint mounted pulley which actuates a given joint. Clockwise or counter-clockwise rotation of the servomotor therefore provides the necessary motion for the fingers and thumb. Adjustment screws in the actuator housing maintain cable tension.

Another key area in this design is the palm. In the top view, notice that where the fingers meet the palm has a curve similar to the human hand. The auxiliary view shows another human-like curvature of the palm. Although the two degree-of-freedom wrist is shown, the motors and pulley drive system for it are not. The wrist will use standard industrial motors as opposed to the Futaba servos because of torque requirements. These systems were under development at the time this document was written. The entire package is designed to fit on the end of a variety of industrial robots. Further specifications on the mechanical structure are in section 5.

An overall system diagram is shown in Figure 2. The complete system consists of an IBM PC/AT or compatible microcomputer, an interface board, and the Anthrobot. The interface board is a pulse generator board which sends the appropriate signals to the Futaba servos. Eventually, the hand will include electronics such that any system (IBM, Macintosh, VME, etc.) with an analog/digital I/O board can run the hand. Optionally, operation of the hand in a master/slave mode is available via an Exos Dexterous Hand Master or a Nintendo Power Glove (see section 7 and Appendices A and B).

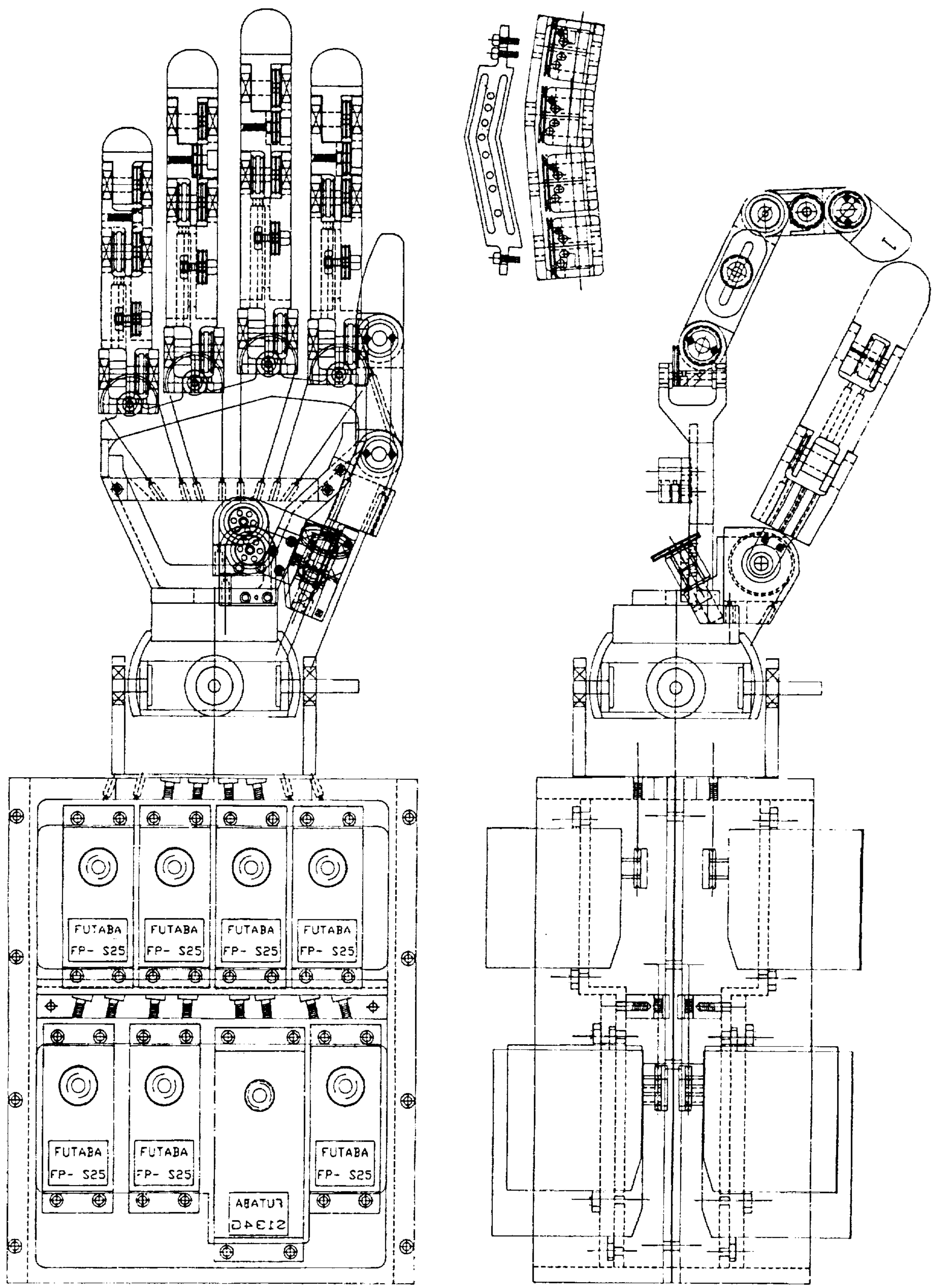

Figure 1. The Anthrobot-2.

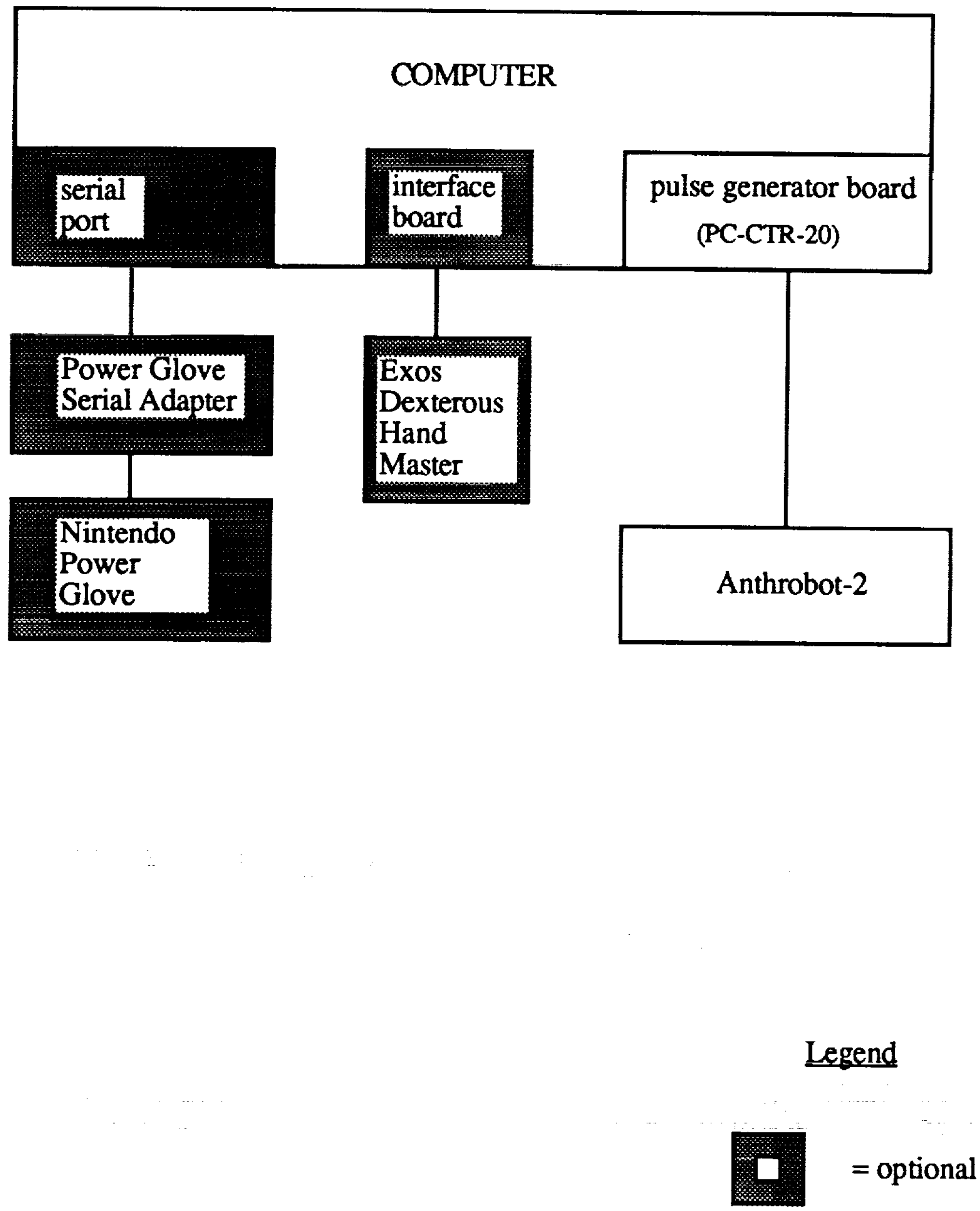

Figure 2. System Overview.

4.0 SPECIFICATIONS

This section lists the preliminary design specifications for the Anthrobot-2. These specifications are subject to revision and verification, pending system assembly and test.

4.1 Hand Specifications

Degrees of freedom: 20
(16 controllable)
Finger and thumb joint specs:
range of motion:
same as human hand
finger tip force: 2.2 lbs./finger
thumb tip force: 6.3 lbs.
hook grip force: 4.5 lbs./finger
(ex: holding a briefcase)
Finger joint bandwidth: 3 Hz
Motor power consumption:
all fingers loaded: 40W (5V@ 8 A)
no load: < 5W (5V @1 A)
Feedback: position servo in each package
(provided by Futaba)
Weight: 1.75 lbs.

4.2 Wrist Specifications

Degrees of freedom: 2
(yaw and pitch)
Yaw joint specs:
range of motion: +/- 20 deg.
torque: 50 lb.-in.
speed: 170 deg./sec. (no load)
Pitch joint specs:
range of motion: +/- 60 deg.
torque: 50 lb.-in.
speed: 170 deg./sec. (no load)
Joint bandwidth: 10 Hz
Motor power consumption:
to be determined (TBD)
Feedback: incremental encoders
Weight: TBD
(estimate 4 lbs. including motors)

5.0 MECHANICAL DESCRIPTION

The Anthrobot is designed to have the same size and shape as the human hand. The linkage proportions are based on data from the U.S. Air Force (see Garrett [1971]), the U.S. Army (Gordon et al. [1989]), and some in-house measurements. The proportions reflect those given for the 50th percentile male armed forces recruit. The dimensions for the hand (not including the actuator housing and wrist) are:

1. Length: 7.5 in.
2. Width: 3.5 in.
3. Thickness: 1.1 in. max.

The entire package-meaning the hand structure, wrist, and actuators-will fit on the end of a variety of industrial manipulators. The package weight is about 10 pounds. The mechanical structure currently is 6061-T6 aluminum. The use of other materials (plastics, space alloys, etc.) is possible. Optionally, fingertips made of a urethane/leather laminate can replace the aluminum fingertips. The tendons consist of 0.025-inch-diameter Technora fiber cables sheathed in Teflon tubing. The Technora fiber has an ultimate tensile strength of 150 pounds. An epoxy resin bonds the Technora fiber to the finger joint pulleys. The tendons are housed in coiled steel springs which attach to the structure of the fingers.

6.0 ELECTRONICS DESCRIPTION

6.1 Servomotor Packages

6.1.1 Finger and Thumb Servos

As shown in Figure 1, the hand uses 14 Futaba FP-S125 servo motors for the fingers and two of the thumb joints. Two of the more powerful Futaba S134G motors control the remaining two axes of the thumb. The servos have the following features (see Futaba [1989]):

FP-S125 Arm-type sail control servo
rotation: 140 degrees (max.)
size: 0.88" X 1.75" X 1.69"
weight: 2.3 oz.
output torque: 129.3 oz./in.
speed: 0.62 sec./60 degrees

FP-S134G Quarter scale retract
rotation: 140 degrees (typ.)
size: 1.14" X 2.32" X 1.97"
weight: 2.8 oz.
output torque: 173.8 oz./in.
speed: 0.33 sec./60 degrees

The servo package includes a motor , gear train, a potentiometer, and servo electronics. A position command consists of sending a pulse of the proper duration every 1/60 second. The PC therefore controls the servos in an open-loop fashion. Our eventual plan is to remove the Futaba servo electronics and close-loop control the servo package via an analog and digital I/O board in a PC or any other similarly equipped computer system.

6.1.2 Wrist Servos

The wrist servomotors are currently under development.

6.2 Pulse Generator Board

The pulse generator board (the PC-CTR-20) creates the pulses needed to command the Futaba servos. The board is a commercially available unit from OMEGA Engineering, Inc. which plugs into the backplane slot of any IBM PC or compatible. The board contains four AMD9513 counter/timer chips with five counter/timers each, for a total of 20 outputs. The board has a number of modes which enable it to perform a variety of pulse generation, pulse timing, and interrupt functions. Commanding the Futaba servos requires the so-called "mode J." In this mode, two registers for each output define the width of the pulse and the frequency at which pulses are sent. The frequency of the pulses is a constant-typically 60-80 Hz (every 16-14 ms). The width of the pulse is the commanded position. For the FP-S125, a width varying between 1 and 2 ms wide corresponds to a position of -/+ 70 degrees. OMEGA [1989] gives more information on the PC-CTR-20 board and the modes.

6.3 Computer

The computer is an IBM PC compatible. The main reason for using a PC was the availability of the pulse generator board for the PC (see previous section). The microprocessor is a 20-MHz 80286. This processor is adequate for the current system which controls the servos by open-loop. Eventually, the microcomputer will close the position loops. We expect to close these loops (a total of sixteen) with a bandwidth of 5 to 10 Hz. The processing ability of the 80286 should be adequate for this requirement. Closing the loops requires replacing the pulse generator board with an analog/digital I/O board. This type of board is available for PCs as well as Macintoshes, Suns, Multibus I and II, VME cages, and many other computer systems. The hand controller will therefore not have to be a PC. Instead, it can be any platform that has enough computational power and is compatible with the user's existing systems.

7.0 SOFTWARE DESCRIPTION

The software is written in 'C'. The standard package consists of two modules. The first module initializes the counter board. The second module controls the width of the generated pulses by writing the appropriate register on the counter board. Optional modules interface the Anthrobot with the Nintendo Power Glove and the Exos Dexterous Hand Master. These modules allow the user to operate the hand in a master/slave mode. Each optional module consists of three routines: an initialization routine, the routine to read the input data from the master, and the routine to map the input commands to the outputs for the Anthrobot. Sections 7.1 and 7.2 describe the operation of the master/slave mapping routines for the Nintendo and the Exos masters, respectively. See the Appendices for descriptions of the Nintendo and Exos products.

7.1 Controlling the Anthrobot with the Nintendo Power Glove

Without the ability to resolve individual finger joint motions, and only three detectable positions per finger, the Power Glove can only provide coarse control of the hand. In effect, four inputs have to control sixteen joints. The input from the master ring finger controls both the slave's ring and pinky fingers. The remaining inputs are assumed to be commands to curl or uncurl the appropriate finger and/or thumb. The flex data therefore provides motion commands for the last three joints on each finger (remember that the middle joint on each finger is mechanically connected to the distal joint). The glove-mounted keyboard controls the remaining side-to-side motion of the fingers. The keyboard can also control the wrist motors.

7.2 Controlling the Anthrobot with the Exos Dexterous Hand Master

The key to controlling the hand using the Exos master is to map the readings from the Hand Master into the appropriate joint commands for the hand. Since the Anthrobot-2 is essentially a scaled replica of a human hand, the map is linear:

$$y=mx+b$$

where:
y is the slave joint position,

x is the glove reading,
m is the scale factor, and
b is a constant offset.

The calibration procedure consists of putting the master and slave in a variety of matching poses, finding the x's and y's, and solving for m and b using standard least-squares methods.

8.0 CONCLUSION

The Anthrobot-2 is a five-fingered, fully functional robot hand. The Anthrobot-2 is the first robot hand to follow human anatomical construction. This includes the link proportions, the thumb motion, and the the shape of the palm. By following the human model, the Anthrobot will exhibit the same dexterous manipulation capabilities as the human hand. In addition, teleoperated control of the Anthrobot is straightforward and intuitive, since the user utilizes the knowledge gained from controlling his or her own hands.

The Anthrobot-2 attaches to a variety of industrial manipulators. One of the first experiments will be to run the hand in master/slave mode to learn what advantages and disadvantages this design has over other end effector designs. In the future, the Anthrobot will have tactile sensing capability added to increase its utility.

APPENDICES

A. The Nintendo Power Glove

The Nintendo Power Glove (PG) is a device used to measure hand and finger motion for games using the Nintendo system. VPL Research in Redwood, California (see List of Contacts), provides the glove with a serial adapter, called the Power Glove Serial Adapter (PGSA), for research use. Using the PGSA, any computer with a serial port can read the information from the glove. The glove information consists of flex data from the thumb and three fingers (the pinky finger does not have a sensor). The flex data is digitized into two-bit values for a total of three positions per finger (0,1,2). The glove also provides its 3-D position relative to a base unit (usually mounted to a TV set). Lastly, the glove information lists which of the several keys on the glove-mounted keyboard have been hit.

The PGSA will upload a new data packet approximately 30 times per second. This is the maximum rate at which the PG can calculate and assemble a new data packet. The PGSA sends a data packet consisting of 10 bytes preceded by 2 header bytes (used for data synchronization). The remaining bytes contain sonar data, finger flex data, and keyboard button selection data.

A.G.E. [1990] provides more information on the Power Glove and the serial adapter. This document is now available from VPL Research.

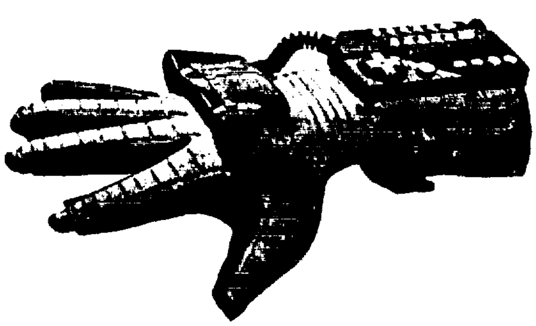

Figure A. The Power Glove.

B. The Exos Dexterous Hand Master

The Dexterous Hand Master (DHM), available from Exos Corporation, is intended to attach to a person's hand and perform direct readings of any joint of that hand. Exos also provides an optional attachment to measure wrist motion. The sensors are hall effect devices mounted on the structure near each joint. The hall effect sensors provide a sinusoidal voltage output proportional to the joint rotation. The sensor is positioned such that the range of motion is roughly within the most linear portion of the sine curve. An electronics board made by Exos provides the power and sensing for the DHM. The board is made for IBM PCs and compatibles. Exos provides 'C' and Assembler routines for activating and reading from the electronics board. Using the Exos software and hardware, the maximum sample rate is 100 Hz. For more information, see Exos [1990a], Exos [1990b], and Marcus and Churchill [1988].

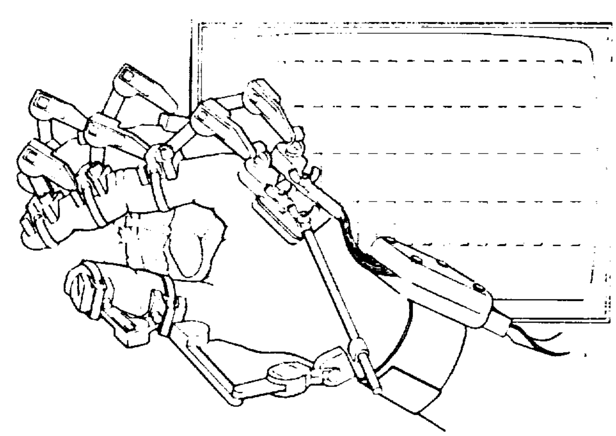

Figure B. The Exos Dexterous Hand Master

C. Comparison with Other Robot Hands

Table C lists hands with four or more fingers, including the Anthrobot, and summarizes their various characteristics. Due to the nature of these devices, they are constantly being upgraded. The reader is urged to contact the appropriate location directly for the latest specifications.

Table C. Comparison of Robot Hands.

	#joints/ finger	#joints thumb	Total #joints	Reference	actuator bandwidth	Sensing	Comments
Anthrobot	4	4	20	This document	3 Hz	1) position sensing at actuator	1) has 2 DOF wrist 2) entire package, including actuators, mounts on end of robot arm 3) has 4 fingers and a thumb 4) last joint of each finger (except thumb) is connected to the previous joint, therefore the total controllable DOF= 16
Utah/MIT	4	4	16	Jacobsen, et.al. [1986]	20 Hz	1) tendon tension 2) position sensing at finger joint	1) no wrist 2) actuators don't mount on arm, need remotizer which restricts range of motion of robot arm 3) has 3 fingers and a thumb 4) non-anatomic thumb placement
Belgrade/ USC	3	2	16	Bekey, et. al. [1990]	0.6 Hz	1) position sensing at base of fingers w/ two for thumb 2) tactile sensing at fingertips	1) no wrist 2) implements a minimal set of grasps 3) has 4 motors-- 2 for thumb, and 2 for each pair of fingers so total controllable DOF = 4. 4) non-anatomic thumb placement 5) has 4 fingers and thumb 6) can mount on end of robot arm
Dexter 3B	4	4	20	Smallridge [1989]	2 Hz	1) no position sensing (uses stepper motors)	1) has a 2 DOF wrist 2) currently used for sign language 3) not mountable on robot arm (actuator package too large) 4) has 4 fingers and thumb 5) tendons are run external to fingers
JPL	4	4	16	Jau, Bruno [1990]	(?)	(?)	1) has wrist 2) for space teleop use 3) mounts to robot arm 4) has 3 fingers and thumb 5) controllable DOF: (?)
Mark-1	4	4	20	Maeda [1989]	5 Hz	1) position sensing at actuator	1) has 2 DOF wrist 2) entire package, including actuators, mounts on end of robot arm 3) has 4 fingers and a thumb 4) last joint of each finger (except thumb) is connected to the previous joint, therefore the total controllable DOF= 16

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Report Documentation Page

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15. Supplementary Notes

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16. Abstract

The Anthrobot-2 is an anatomically correct, fully functioning robot hand. The number of fingers, the proportions of the links, the placement and motion of the thumb, and the shape of the palm follow those of the human hand. Each of the finger and thumb joints are servo controlled. The Anthrobot-2 also includes a two-degree-of-freedom wrist. The entire package, including wrist, hand and actuators, will mount on the ends of a variety of industrial manipulators. A patent has been applied for on the design. The Anthrobot-2 will be useful in tasks where dexterous manipulation or telemanipulation are required.

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